

DESCRIPTION

Method for Manufacturing Optical Element of Refractive Index
Distribution Type

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TECHNICAL FIELD

The present invention relates to a method of producing
a graded refractive index optical element.

BACKGROUND ART

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In the field of optical communications, optical fiber
collimators are conventionally used to emit signal light, which
has been transmitted through an optical fiber, in the form of
parallel light from the optical fiber, or in reverse, used to
converge parallel light on one end surface of an optical fiber to
15 cause the light to enter the optical fiber. When using such an
optical fiber collimeter, interposition of an optically
functional element (for example, an optical filter, optical
isolator, optical switch, optical modulator, etc.) between a pair
of collimator lenses can provide a desired effect on the signal
20 light transmitted through a single mode optical fiber at the
light-entering side and then converge the signal light to further
transmit the light to a single mode optical fiber at the light-
receiving side.

Various forms of lenses have been used as collimating
25 lenses for optical fiber collimators. However, cylindrical graded
refractive index lenses (also referred to as "rod lenses" or
"GRIN lenses") are generally used because of their ease of
polishing and like processing during manufacture, compared to
spherical lens and complicated non-spherical lenses. Such graded
30 refractive index lenses work as lenses, for example, converging
light, because the interior of the rod glass has a continuous
refractive index distribution in the radial direction from the
center.

To produce such graded refractive index lenses, ion-
35 exchange methods, double crucible methods, CVD methods (vapor-

phase deposition methods), sol-gel methods, rod-in-tube methods, and like methods are known as techniques for forming a graded refractive index distribution in the radial direction of a glass rod. Among these, ion exchange is the most typical method for
5 producing a graded refractive index lens and comprises immersing a homogeneous glass rod into a molten salt containing a monovalent cation (e.g., K^+ , Tl^+ , Ag^+) to exchange a monovalent cation in the glass (e.g., Na^+) for the monovalent cation in the molten salt, thereby forming a graded refractive index
10 distribution. For example, Patent Document 1 discloses a method of producing a graded refractive index lens comprising subjecting a Na-containing glass rod to ion exchange using a molten salt containing Ag^+ to form a graded reflective index distribution in the radial direction of the rod.

15 Microlens arrays comprising an array of lenses with a diameter of about several tens of micrometers to submillimeter, each lens having a graded refractive index distribution formed by subjecting a planer glass to ion exchange, are being used as computer board connectors or light source collimators.

20 When a graded refractive index lens is produced by an ion exchange method, the temperature of the molten salt used is usually in the range of about 250°C to about 400°C, and the manufacturing facility costs less than that of vapor-phase methods such as CVD. Moreover, compared to manufacturing
25 spherical lenses, ion exchange methods are advantageous in terms of ease of polishing. However, conventional ion exchange methods have problems as below:

 The first problem is the control of conditions of the molten salt at the time of ion exchange. The ion exchange rate
30 and the rate of ion diffusion in a glass substrate depend on the temperature of the molten salt. The liquid phase temperature of the molten salt depends on the mixing ratio (composition) of the molten salt, and the ion exchange temperature can be controlled only at temperatures not lower than the liquid phase temperature
35 of the molten salt. Therefore, there are cases in which the

concentration of ions in the molten salt and the ion exchange temperature cannot be controlled independently. Therefore, to produce a graded refractive index lens having a desired refractive index profile by an ion exchange method, it is not
5 easy to select the appropriate ion exchange conditions such as the molten salt composition, temperature, immersion time, etc., and a high level of expertise is needed. Furthermore, when using ions that are prone to oxidation in air, ion exchange needs to be performed in a reducing atmosphere. These problems are
10 encountered not only in the production of graded refractive index lenses but are also common problems in the production of graded refractive index optical elements by introducing a graded refractive index distribution into a glass substrate.

The second problem is the application of an ion
15 exchange-blocking film. When ion exchange is performed using a molten salt, it is necessary to apply an ion exchange-blocking film over the entire substrate except the portion where a graded refractive index distribution is to be formed. Photolithography is generally used to apply an ion exchange-blocking film, but
20 formation of such a blocking film requires a complicated process. This is also a common problem in the production of graded refractive index optical elements by introducing a graded refractive index distribution into a glass substrate.

Patent Document 1: Japanese Unexamined Patent Publication No.
25 2001-159702

DISCLOSURE OF THE INVENTION

PROBLEMS TO BE SOLVED BY THE INVENTION

A primary object of the present invention is to provide a method of producing a graded refractive index optical element,
30 the method being capable of easily forming a graded refractive index distribution in a desired portion of a glass substrate without the need for a specific treatment atmosphere and without using a molten salt.

MEANS FOR SOLVING THE PROBLEM

35 The present inventors carried out extensive research to

achieve the above object. As a result, it was found that when using a production method comprising diffusing copper ions into a glass substrate using a specific paste containing a copper compound to form a different refractive index region in the glass substrate, the above object can be achieved. The present invention has been accomplished, based on this finding.

More specifically, the present invention relates to the following methods of producing graded refractive index optical elements.

1. A method of producing a graded refractive index optical element comprising applying a paste containing a copper compound, an organic resin and an organic solvent to a glass substrate containing an alkali metal component as a glass component and then performing heat treatment at a temperature below the softening temperature of the glass substrate.
2. The method according to item 1 wherein the graded refractive index optical element is a lens, lens array or diffraction grating.
3. The method according to item 1 or 2 wherein the glass substrate is made of a glass containing at least 2% by weight of alkali metal, calculated on an oxide basis, the glass being a silicate glass, borosilicate glass, phosphate glass, or fluorophosphate glass.
4. The method according to item 3 wherein the glass substrate is a borosilicate glass substrate containing 40 to 82% by weight of SiO_2 , 12 to 50% by weight of B_2O_3 , 2 to 25% by weight of at least one member selected from Na_2O , K_2O , Li_2O , Rb_2O and Cs_2O ; not more than 25% by weight of at least one member selected from MgO , CaO , BaO , ZnO , SrO and PbO ; not more than 20% by weight of at least one member selected from Al_2O_3 , La_2O_3 , Y_2O_3 , Ta_2O_3 and Gd_2O_3 ; not more than 10% by weight of at least one member selected from Nb_2O_5 and ZrO_2 ; not more than 5% by weight of at least one member selected from As_2O_3 , Sb_2O_3 and SnO ; and 0.05 to 10% by weight of at least one member selected from Cl, Br and I.
5. A graded refractive index optical element produced by the

method of any one of items 1 to 4.

6. The graded refractive index optical element according to item 5 which is a lens, lens array or diffraction grating.

5 The method of producing a graded refractive index optical element according to the invention is described below in detail. The graded refractive index optical element of the invention refers to an element that exhibits a desired optical property by utilizing a region formed in at least a portion of a
10 glass substrate, the region having a refractive index distribution different from that of the rest of the substrate. Specific examples of such optical elements include graded refractive index lens, graded refractive index lens arrays, diffraction gratings, and the like.

15 In the method of the invention, it is necessary to use a glass substrate containing an alkali metal component as a glass component.

 Examples of the alkali metal component contained in the glass substrate include Li, Na, K, Rb, Cs, etc. Among these, Li, Na, K, etc. are preferable, and Na is particularly preferable.
20 Such alkali metals may exist in an ionic state, or may exist as an oxide. Such alkali metals may be used singly or as a combination of two or more such metals.

 The alkali metal content of the glass substrate is
25 suitably at least about 2% by weight, preferably at least about 5% by weight, and more preferably at least about 10% by weight, calculated on an oxide basis. Although the maximum alkali metal content of the glass substrate is not particularly limited, the maximum content is suitably about 40% by weight, preferably about
30 30% by weight, and more preferably about 20% by weight, calculated on an oxide basis.

 In the present invention, any glass containing an alkali metal component can be used without particular limitation. For example, a silicate glass, borosilicate glass, phosphate
35 glass, fluorophosphate glass, etc. can be used.

The compositions of such glasses for use are not particularly limited. Any glass containing an alkali metal as described above and having a known silicate glass, borosilicate glass, phosphate glass, fluorophosphate glass or like glass composition can be used without particular limitation.

Specific examples of such glass compositions include the following compositions shown in 1) to 4), calculated on an oxide basis:

1) silicate glass containing 40 to 80% by weight, and preferably 50 to 75% by weight, of SiO_2 ; 5 to 25% by weight, and preferably 17 to 20% by weight, of CaO ; 5 to 25% by weight, and preferably 7 to 20% by weight, of at least one member selected from Na_2O , K_2O , Li_2O , Rb_2O and Cs_2O ; not more than 2% by weight, and preferably not more than 1.5% by weight, of at least one member selected from MgO , BaO , ZnO , SrO and PbO (the minimum amount is preferably about 0.1% by weight to fully achieve the desired effects); not more than 15% by weight, and preferably not more than 10% by weight, of Al_2O_3 (the minimum amount is preferably about 0.5% by weight to fully achieve the desired effects); and not more than 3% by weight, and preferably not more than 1% by weight, of at least one member selected from Fe_2O_3 and SO_3 (the minimum amount is preferably about 0.05% by weight to fully achieve the desired effects);

2) borosilicate glass containing 20 to 80% by weight, and preferably 30 to 75% by weight, of SiO_2 ; 3 to 50% by weight, and preferably 5 to 30% by weight, of B_2O_3 ; 2 to 20% by weight, and preferably 5 to 15% by weight, of at least one member selected from Na_2O , K_2O , Li_2O , Rb_2O and Cs_2O ; not more than 30% by weight, and preferably not more than 25% by weight, of at least one member selected from MgO , CaO , BaO , ZnO , SrO and PbO (the minimum amount is preferably about 1% by weight to fully achieve the desired effects); not more than 15% by weight, and preferably not more than 10% by weight, of at least one member selected from Al_2O_3 , La_2O_3 , Y_2O_3 , Ta_2O_3 and Gd_2O_3 (the minimum amount is preferably about 0.5% by weight to fully achieve the desired

effects); not more than 2% by weight, and preferably not more than 1% by weight, of at least one member selected from Nb_2O_5 and ZrO_2 (the minimum amount is preferably about 0.05% by weight to fully achieve the desired effects); and not more than 2% by weight, and preferably not more than 1% by weight, of at least one member selected from As_2O_3 , Sb_2O_3 and SnO (the minimum amount is preferably about 0.01% by weight to fully achieve the desired effects);

3) phosphate glass containing 40 to 80% by weight, and preferably 50 to 75% by weight, of P_2O_5 ; not more than 20% by weight, and preferably not more than 10% by weight of, SiO_2 (the minimum amount is preferably about 0.5% by weight to fully achieve the desired effects); 2 to 20% by weight, and preferably 5 to 15% by weight, of at least one member selected from Na_2O , K_2O , Li_2O , Rb_2O and Cs_2O ; 2 to 50% by weight, and preferably 5 to 45% by weight, of at least one member selected from the group consisting of MgO , CaO , BaO , ZnO , SrO and PbO ; not more than 15% by weight, and preferably not more than 10% by weight, of at least one member selected from B_2O_3 , Al_2O_3 , La_2O_3 , Y_2O_3 , Ta_2O_3 , Nd_2O_3 and Gd_2O_3 (the minimum amount is preferably about 0.5% by weight to fully achieve the desired effects); and not more than 2% by weight, and preferably not more than 1% by weight, of at least one member selected from Nb_2O_5 and ZrO_2 (the minimum amount is preferably about 0.01% by weight to fully achieve the desired effects); and

4) fluorophosphate glass obtained by substitution of F (fluorine) for some of the O (oxygen) of an original composition containing 20 to 50% by weight, and preferably 30 to 40% by weight, of P_2O_5 ; 5 to 30% by weight, and preferably 10 to 25%, of Al_2O_3 ; 2 to 20% by weight, and preferably 5 to 15% by weight, of at least one member selected from Na_2O , K_2O , Li_2O , Rb_2O and Cs_2O ; and 10 to 50% by weight; and preferably 20 to 40% by weight, of at least one member selected from MgO , CaO , BaO , ZnO and SrO .

The form of such a glass substrate is not particularly limited and can be suitably determined according to the purpose

of the final product. For example, a wide variety of forms suitable for lenses, lens arrays, and diffraction gratings can be used, and specific examples thereof are plates, cylindrical columns, rectangular columns, and the like. For example,

5 substrates formed into a desired shape by grinding a mass of glass having a composition as described above, and substrates formed by molding a molten glass into a desired shape and then optionally polishing may be used.

10 The method of the present invention comprises applying a paste containing a copper compound to such a glass substrate containing an alkali metal component as a glass component, and performing heat treatment at a temperature below the softening temperature of the glass substrate.

15 The paste for use is one obtained by dispersing a copper compound and an organic resin in an organic solvent and forming a paste. Any such paste can be used as long as the paste has a viscosity that allows its application to a glass substrate and it contains a copper compound capable of diffusing copper ions by heat treatment. More specifically, the paste viscosity
20 can be suitably selected in consideration of the application method, paste composition, diffusion conditions into the substrate, etc.

The copper compound contained in the paste is diffused into the glass substrate as copper ions by ion exchange with an
25 alkali metal component of the glass substrate by applying the paste to the glass substrate and performing heat treatment. The portion containing such dispersed copper ions has a refractive index different from that of the rest of the glass substrate, the refractive index having a continuous distribution that varies
30 according to the concentration of diffused ions. Although copper ions can be monovalent or divalent cations, the copper contained in the paste is presumably diffused mainly as monovalent cations. This is presumably because the organic resin contained in the
35 paste is carbonized to produce a reducing atmosphere, by which monovalent copper ions are formed.

The copper compound contained in the paste is not particularly limited as long as it is an ionic copper compound capable of diffusing copper ions into a glass substrate by heat treatment, and may be a monovalent or divalent copper compound.

5 Examples of such copper compounds include inorganic salts.

Specific examples of such copper compounds include CuSO_4 , CuCl , CuCl_2 , CuBr , CuBr_2 , Cu_2O , CuO , $\text{Cu}(\text{NO}_3)_2$, CuS , CuI , $\text{Cu}(\text{NO}_3) \cdot 3\text{H}_2\text{O}$, etc. Among these, CuSO_4 , $\text{Cu}(\text{NO}_3)_2$, and the like are preferable. Such copper compounds can be used singly or as a
10 combination of two or more such compounds.

The organic resin to be contained in the paste is one that decomposes at the heat treatment temperature. Preferable are resins that are capable of easily producing a reducing atmosphere by their decomposition and carbonization and easily removable by
15 washing with water. Examples of such resins include cellulose resins, methyl cellulose resins, cellulose acetate resins, cellulose nitrate resins, cellulose acetate butyrate resins, acrylic resins, petroleum resins, etc. Such organic resins can be used singly or as a combination of two or more such resins.

20 The organic solvent used in the paste is preferably a solvent in which a copper compound and an organic resin can be easily dispersed and which easily volatilizes when dried. More specifically, a solvent that is a liquid at room temperature (about 20°C) and volatilizes at a temperature of about 50°C to
25 about 200°C is preferable. Examples of such solvents include alcohols such as methanol, ethanol, etc.; dimethyl ether; ketones such as acetone, etc.; and so on.

Although the content of each component in the paste is not particularly limited, the amount of organic solvent is
30 usually about 5 to 30 parts by weight, and preferably about 7 to about 25 parts by weight, and the amount of resin component is usually about 20 to about 55 parts by weight, and preferably about 25 to about 45 parts by weight, per 100 parts by weight of copper compound.

35 If necessary, additives may be incorporated into the

paste. For example, Na_2SO_4 , K_2SO_4 , NaNO_3 , KNO_3 , NaCl , NaBr , KCl , KBr , NaI , KI , etc. can be used as additives to lower the melting point of the copper compound. Among these, Na_2SO_4 , K_2SO_4 , NaNO_3 , KNO_3 , and the like are preferable. Although the amount of such
5 additives is not particularly limited, the amount may be about 5 to about 25 parts by weight, and preferably about 10 to about 20 parts by weight, per 100 parts by weight of copper compound.

According to the method of the invention, the paste is first applied to a glass substrate. The shape of the applied
10 paste is not particularly limited and can be suitably arranged according to the properties of the optical element. For example, when a graded refractive index lens is produced, the paste may be applied to a desired portion of the substrate to form a shape usable as the lens. More specifically, when the paste is applied
15 as circle(s), the radius of the circle(s) is usually about 5 μm to about 1 mm, and preferably about 10 μm to about 0.5 mm. When a lens array is produced, the patterning interval, circle or dot size, etc. can be suitably adjusted according to the desired lens pattern. Although the patterning interval is not particularly
20 limited, it is usually 1 cm or less, preferably 500 μm or less, and more preferably 250 μm or less.

The method of application is not particularly limited, and known application methods can be suitably used. For example, methods such as spin coating, spray coating, dip coating, etc.
25 can be used. When a graded refractive microlens is produced, the paste may be dropped onto the substrate using a syringe, a dispensing pipette, or the like, or printing techniques for forming precise circular microdots (for example, ink-jet printing) may be used.

30 When a diffraction grating is produced, linear patterning may be used. For linear patterning, screen printing as used in dyeing, etc. may be used. When forming a linear pattern, the line width may be suitably determined according to the desired properties of the optical element (diffraction grating).
35 The line width is usually 500 μm or less, preferably 200 μm or

less, and more preferably 100 μm or less. To form a very precise pattern, a process comprising patterning a glass substrate surface using an inorganic film according to a photolithographic method and then applying a paste containing a metal compound to
5 the exposed portion of the glass substrate may be used.

In all the above paste application methods, the thickness of the applied paste is not particularly limited and can be suitably determined according to the type, amount, etc. of copper compound contained in the paste. The thickness, however,
10 is usually 2 mm or less, preferably 1.5 mm or less, and particularly preferably 1 mm or less.

After applying the paste, the resulting coating film is usually dried prior to heat treatment. The drying conditions are not particularly limited as long as the film is dried so that the
15 solvent component is sufficiently removed and the paste is dried to a solid. Usually, the coating film can be efficiently dried by heating at a temperature of about 100°C to about 250°C for about 30 minutes to about 1.5 hours, and preferably at a temperature of about 150°C to about 200°C for about 45 minutes to about 1 hour.

Subsequently, the dried coating film is heat-treated. The heat treatment temperature is usually in the range of about 300°C to about 600°C, and preferably in the range of about 350°C to about 550°C, being set at a temperature below the softening
20 temperature of the glass substrate. Although the heat treatment time can be suitably determined according to the temperature, it is usually about 10 minutes to about 100 hours, preferably about 30 minutes to about 50 hours, and particularly preferably about 1 to 25 hours. The heat treatment atmosphere is usually an oxygen-containing atmosphere, such as in air.

Heat treatment by the above-mentioned method allows
30 copper ions to diffuse into the glass substrate. The diffused copper ions exist as Cu^+ ions, Cu_2O , copper metal fine particles, etc., depending on the treatment conditions. As a result, the portions containing such dispersed copper ions differ in
35 refractive index from the rest of the glass substrate. The

refractive index distribution is continuous, and usually, the refractive index at the substrate surface onto which the paste has been applied has the greatest refractive index. The greater the diffusion depth, the smaller is the refractive index. After
5 heat treatment, the substrate is usually allowed to cool to room temperature, and the paste residue remaining on the substrate is washed away with water.

In the production of graded refractive index lenses and refractive index lens arrays by the above method, especially when
10 using as the glass substrate a borosilicate glass substrate containing 40 to 82% by weight of SiO_2 , 12 to 50% by weight of B_2O_3 , 2 to 25% by weight of at least one member selected from Na_2O , K_2O , Li_2O , Rb_2O and Cs_2O ; not more than 25% by weight of at least one member selected from MgO , CaO , BaO , ZnO , SrO and PbO (the
15 minimum amount is preferably about 2% by weight to fully achieve the desired effects); not more than 20% by weight of at least one member selected from Al_2O_3 , La_2O_3 , Y_2O_3 , Ta_2O_3 and Gd_2O_3 (the minimum amount is preferably about 5% by weight to fully achieve the desired effects); not more than 10% by weight of at least one
20 member selected from Nb_2O_5 and ZrO_2 (the minimum amount is preferably about 1% by weight to fully achieve the desired effects); not more than 5% by weight of at least one member selected from As_2O_3 , Sb_2O_3 and SnO (the minimum amount is preferably about 0.5% by weight to fully achieve the desired
25 effects); and 0.05 to 10% by weight of at least one member selected from Cl, Br and I, the copper ions diffusing into the glass substrate react with at least one kind of halogen atom selected from Cl, Br and I contained in the glass substrate, thus giving copper halide(s). The dispersion of the copper halide(s)
30 imparts ultraviolet absorption effects, improved laser processability, etc. to the interior of the glass.

Graded refractive index optical elements such as graded refractive index lenses, graded refraction index lens arrays, and diffraction gratings can be produced by the above-mentioned
35 process.

For example, graded refractive index lenses can be used for laser beam focus correction, optical coupling between optical fibers, and like purposes. Graded refraction index lens arrays can be used for optical branching in optical communications,
5 parallel image processing, etc. Refraction diffraction gratings can be used for sensor elements, etc.

EFFECT OF THE INVENTION

According to the method of the invention, a continuously varying refractive index distribution can be
10 provided in a desired portion of a glass substrate by simply applying a paste containing a copper compound to a glass substrate containing an alkali metal component and heating in an atmosphere such as air. This method does not require a specific treatment atmosphere (for example, a reducing atmosphere), etc.,
15 so that a graded refractive index lens can be produced at low cost without a complicated production process.

Moreover, since the method does not use a molten salt, strict control over a molten salt is not necessary, and the heat treatment temperature and the copper compound concentration in
20 the paste can be controlled independently. Furthermore, unlike immersion in a molten salt, since the paste is applied to a desired portion of the substrate, it is not necessary to mask the substrate surface with a blocking film, etc.

BRIEF DESCRIPTION OF THE DRAWINGS

25 Fig. 1 is a graph of EDX line scanning results, showing the relationship between the distance in the radial direction from the center of the graded refractive index lens obtained in Example 1 and the amount of copper diffused therein.

Fig. 2 is a graph showing the relationships between the
30 depth from the substrate surface and the amount of copper diffused and the refractive index, at the center of the graded refractive index lens obtained in Example 1.

Fig. 3 is a pattern diagram of the patterning of the paste used in the production of the graded refractive index
35 microlens array of Example 2. The diameter of the paste-applied

circles is 200 μm , and the patterning interval between the paste-applied circles is 300 μm .

BEST MODE FOR CARRYING OUT THE INVENTION

The present invention is described in further detail
5 with reference to the following Examples. However, the present invention is not limited to the Examples.

Example 1

(Production of a graded refractive index lens)

A commercially available $\text{SiO}_2\text{-CaO-Na}_2\text{O}$ glass (product
10 number: B270, manufactured by Schott) was cut to 10 mm long x 10 mm wide x 3 mm thick, and washed. A paste of 55% by weight of CuSO_4 , 10% by weight of Na_2SO_4 , 15% by weight of acrylic resin, 10% by weight of cellulose resin, and 10% by weight of terpeneol (the paste being prepared by mixing 18.2 parts by weight of
15 organic solvent, 45.5 parts by weight of resin component, and 18.2 parts by weight of additive per 100 parts by weight of copper compound) was applied dropwise using a syringe to one side of the glass to form a circle (radius: 0.1 to 0.2 mm) to a thickness of 0.2 mm.

20 Subsequently, the pasted glass substrate was dried at 200°C for 1 hour, and then heat-treated in air at 510°C for 12 hours.

The copper distribution in the heat-treated sample was determined using an EDX (energy dispersive X-ray analyzer), and
25 it was confirmed that a large amount of copper was distributed (dispersed) within a radius of about 300 μm from the center of the applied paste. Fig. 1 shows the EDX line scanning results.

The copper distribution in the depth direction was also determined using the EDX, and it was confirmed that the copper
30 was distributed to a depth of about 25 μm . The refractive index distribution in the depth direction of the glass substrate was examined, and it was revealed that the maximum refractive index difference from the glass substrate was about 1×10^{-2} , and a graded refractive index distribution extended to a depth of about
35 20 μm from the surface. Fig. 2 shows the relationships between

the depth from the substrate surface and the copper distribution and the refractive index, at the center of the applied paste. The arrows (\leftarrow and \rightarrow) in Fig. 2 indicate which graph corresponds to the refractive index and the detection intensity, respectively.

5 Example 2

(Production of a graded refractive index lens array)

A glass (cut glass) and a paste as in Example 1 were prepared.

10 The paste was applied dropwise using a dispensing pipette to one side of the glass to form 20 by 20 circles (diameter: 200 μm , total 400 dots) with a patterning interval (distance from the center of one circle to the center of the adjacent circle) of 300 μm to a thickness of 1 mm. Fig. 3 shows the pattern diagram of the patterning.

15 Subsequently, the pasted glass substrate was dried at 200°C for 1 hour, and then heat-treated in air at 500°C for 12 hours.

The copper distribution in the heat-treated sample was determined using an EDX (energy dispersive X-ray analyzer), and
20 it was confirmed that copper was distributed in the paste-dropped circle portions. The refractive index distribution in the depth direction of the glass substrate was also examined, and it was revealed that the maximum refractive index difference from the glass substrate was about 1×10^{-2} and a graded refractive index
25 distribution extended to a depth of about 20 μm from the surface.